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Stability-Based Comparison between MRWT & SRWT for Optimized Design of Offshore Wind Farms

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ABSTRACT

The contemporary world is reaching a point of having to look back carefully to reevaluate the damage that has been done to Mother Nature. The increasing pollution and contamination have gotten far beyond safe margins. In contrast, the need for energy is currently escalating. Meanwhile, traditional energy resources like petrol are not only adding to pollution but even are getting consumed and expected to be scarce within decades. Consequently, nations worldwide have realized the common goal of searching for new clean renewable energy resources. It is a matter of time that these renewable energy sources will prevail and become the main sources. The most effective resource of renewable energies is wind. This is attributed to consistent availability in many spots worldwide. Offshore areas may be the best for higher wind momentum. Besides, the escalating land prices redirected experts to vast offshore areas. On putting economic costs into account, an optimized design is thus required to minimize the cost of offshore wind farms together with considering efficiency. Wind turbines can be classified according to number of rotors, Single-Rotor Wind Turbine (SRWT) and Multi-Rotors Wind Turbine (MRWT). This paper compares from a stability-wise scope between existing models of offshore SRWT and MRWT, both with total capacity of 5MW using ANSYS software. Both turbines are considered subjected to similar conditions of wind and wave loads. On studying the stability of the two types together with accounting for costs and investigating comparable loads during storms with extreme conditions, it is shown that MRWT are locally subjected to higher deflections in the rotor fixation spars. However, MRWT could be cheaper as well as easier for transportation. This paper suggests using additional bracing between spars for optimum performance of MRWT and thereby optimum design of wind farms.

Keywords: Wind Turbine, Stability, Rotors, ANSYS, Offshore, Cost, Optimum design.

INTRODUCTION

Energy is essential for life and its continuity. In spite of that, it is preferable that energy resources should be renewable and clean. Many renewable energy resources exist, however, solar, sea waves and wind energies may be the friendliest to environmental life. In addition, wind energy may be the most promising field of energy when it comes to feasibility. This is attributed to the availability worldwide along the calendar year. This is the case since it is produced from variations in temperatures that generate differences in the atmospheric pressure, and that continues to happen all over the globe along the four seasons of the year. Moreover, the technology of wind turbines, which are the units used for transforming wind energy to electrical energy, have been clearly developed along the past decades.

In general, wind turbines can convert kinetic energy of the flowing wind into electrical energy. Included blades produce the aerodynamic lift forces that generate torque as mechanical power. The resulting power is then converted to electrical power using the included generator, and thus producing a clean energy without any emissions. For offshore wind turbines which are constructed within sea water areas, wind is much stronger and has low turbulence at high speeds. This results in increasing the power and efficiency of the produced energy. However, using offshore turbines has some drawbacks including the need for special materials to resist corrosion as well as higher costs for installation and transportation.

The most common type of turbines is the Horizontal Axis Wind Turbines (HAWTs) that considers the rotor rotation about a horizontal axis parallel to the ground together with blades attached to the hub. The Rotor-Nacelle Assembly (RNA) consists of one, two or three rotors fixed to a hub including a generator. The tower, foundation and electrical system are the other major components.

On studying a Multi-Rotor Wind Turbine (MRWT) in contrast to a Single-Rotor Wind Turbine (SRWT), it is shown that there are variations in weight, cost, and dimensions. MRWT has smaller rotors and easier transportation for size issues. In addition, MRWT has the capability to run rotors at variable speeds. In spite of that, assembly complexity is the main drawback of MRWT due to increasing number of components. Using ANSYS software, this paper simulates two cases of wind turbines in operation, SRWT versus a three-rotor MRWT. The studied models are analyzed for stability while being exposed to different types of extreme loads during storm conditions with rotors rotating or not. The analysis also includes the stability in stationary blades for wind speed higher than the cutoff speed when turbine blades are pitched parallel with the wind direction, which is called feathering, and each turbine is in stationary mode. Furthermore, this paper introduces using a suitable bracing for the MRWT model to overcome the unfavorable deformations that the fixing spars of rotors undergo during the studied loading cases.

PROBLEM DEFINITION

Optimum design of offshore wind farms is essential for economical production of clean renewable electrical energy from the flowing wind. Thus, some of the existing disadvantages of SRWT need to be addressed and dealt with. The larger sizes of blades and the rotor size in general, usually lead to bigger costs as well as complexity of installation, and sometimes even difficulties in repairing, maintenance and transportation. In addition, the load distribution on the different parts of such large wind turbines may not be ideal for stress distributions on the main supporting structure including foundations especially during storms. Therefore, it may be advisory to stop going bigger and bigger in SRWT and start thinking of having efficient smaller sizes of turbines as MRWT. The latter type generates the same electric power with smaller parts together with being cheaper as well. However, such MRWT have their own defects. MRWT have more relative deformations in the spars connecting rotors to the nacelles, which may generate more fatigue problems by time as well as having fears of out of phase motions of the different rotors. It is thus essential to study a comparison between the performance of SRWT and MRWT from a stability point of view to get closer to wiser decisions concerning the design of offshore wind farms. Such comparisons should be achieved on considering cruel environments of stormy conditions within offshore areas.

LITERATURE REVIEW

By the first decade of the 21st century, wind power had become the best hope for the future of alternative energy. The new era of wind development was led by the United States during the 1980s, but Europe has overtaken that ranking, accounting for two-thirds of total worldwide wind development since 2001 [1]. Despite the fact that wind energy exists without limitations, yet at no time have humans ever employed more than a tiny fraction of its kinetic energy.

The development of wind mills went through different stages. In 1886, the first one to build a practical large-scale wind turbine was Charles Brush, a scientist from Cleveland, USA. Brush designed and constructed a wind turbine with a tower rising 60 feet (18.3 m). From the tower, a 56 feet rotor (17.1 m) diameter rotated with 144 slender blades. Within the tower, Brush located his dynamo and the necessary gearing to drive it. In the tower basement, Brush installed 12 batteries [2].

In addition, further experimentation took place between 1890 and 1920. However, these decades represented the pause between invention and application. It was only after World War I that some mechanical American engineers applied advances in aeronautics to the design of a practical inexpensive wind turbine [1,2].

From a systematic point of view, airfoil studies began in Denmark in 1892 with la-Cour's wind tunnel evolving in 1900 [1,2]. Moreover, in 1903, Paul la Cour discovered wind turbines with less number of blades to spin faster. By 1906, with the support of the Danish government, 40 wind turbines were generating electricity in Denmark.

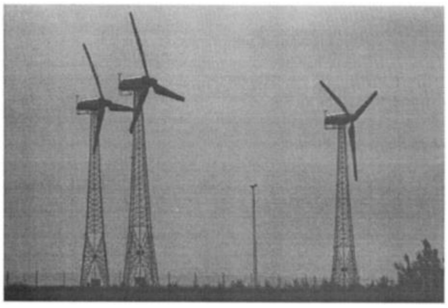


Fig.1: Danish Wind Mills by 1979 [1]

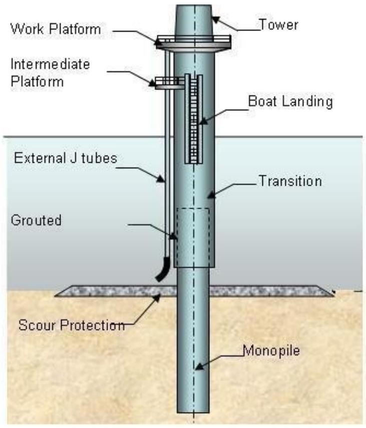


Fig. 2: Offshore monopole foundation

Consequently, by 1908, 72 wind power systems were running across Denmark. The windmills capacities ranged from 5kW to 25 kW. However, nearly 90 turbines were installed during World War II, including the 30-kW Lykkegaard wind turbine patterned after La-Cour’s achievements and Smidth’s more modern "Aeromotors" [2]. Furthermore, in 1957, Johannes Juul, a former student of Paul la-Cour, built a horizontal-axis wind turbine of 200kw with a diameter of 24 meters and 3 blades [2]. In 1991 the first offshore wind farm was developed by DONG Energy, 2.5 km off the Danish coast at Vindeby. The latter offshore wind farm Contained eleven 450 kW turbines for a total capacity of 4.95 MW [3].2

By the start of the 21st century, global wind power capacity reached 17.4 Gega watts, and in only 5 years later, the global capacity multiplied 4 times more. In addition, Under the American Recovery and Reinvestment Act (ARRA) in 2009, $93 million were dedicated to wind power research and development [2]. Currently, Wind power is China’s third-largest source of power, exceeding the nuclear power.

Until 2001, the growth of the offshore wind power sector was irregular and mainly depended on a handful of small near-shore projects in Danish and Dutch waters featuring wind turbines with a capacity of less than 1 MW [3]. In 2001, with 20 turbines and a total capacity of 40 MW, the “Middel grunden” project in Danish waters became the first “utility-scale” offshore wind farm. That same year, seven 1.5 MW turbines were grid connected off Utgrunden in Sweden. Since the beginning of the decade, new offshore wind capacity has been going online every year. Moreover, the share of new offshore wind capacity in total wind capacity additions has been increasing. In 2001 the 50.5 MW of installed offshore capacity represented 1% of the total new

European annual wind energy capacity [3]. The 883 MW total power of offshore farms installed in 2010 represented 9.5% of the annual European wind energy market. At the end of 2010, 45 wind farms spreading across nine European countries were feeding an estimated 10.6 TWh of electricity into the European grid only. Furthermore, by 2013, wind power was found to produce more electricity than any other source in Spain for three months in a row, and is currently providing the country with approximately 25% of its electricity [2].

Wind turbine consists of main components: Rotor, Nacelle and Tower. Rotor consists of hub and blades that transform the kinetic energy of wind to mechanical energy while nacelle which contains gears and a generator. Rotor and nacelle assembly (RNA) are mounted on tower's top. Tower is constructed to support the components of wind turbine. Wind turbines are classified into two main types: horizontal axis and vertical axis. A horizontal axis type (HAWT) has its blades rotating around an axis parallel to the ground. A vertical axis type (VAWT) has its blades rotating around an axis perpendicular to the ground.[4] However, horizontal axis type is more common. The MRWT concept uses more number of small rotors of equivalent swept area to replace a single large rotor. In addition, MRWT has many advantages because of reduced mass of blades as blade weight increases with diameter, therefore reducing cost. Ease of installation, assembly of smaller components and maintenance. Though, Complexity is the main drawback of MRWT due to increasing number of components and the need to a special support to join rotors to tower.

Offshore wind farms are large number of wind turbines which are lied over on bodies of water. Wind is much stronger over water than over land, resulting in increasing power and efficiency. Over water, wind has low turbulence at high speed. However, the placement of enormous wind farms over the open ocean and out of the way has enormous value. Offshore wind turbine needs higher cost and special material to resist corrosion. It is important to take into consideration the foundation of offshore wind turbines for suitable design. There are several bottom-mounted support structures as mono-pile, tripod and jacket foundations. The power curve of a wind turbine indicates its performance which represents the value of generated power with change of wind speed. Moreover, it is important to use power curve to make comparison between models which aids in the selection of the best turbine with optimized characteristics from the available options. Cut-in wind speed at which turbine starts generating power at minimum value, Rated wind speed where turbine generates the rated power and Cut-out wind speed where the maximum value of turbine power occurs before shut down.[5] The capacity factor of wind turbine is defined as the ratio of the average power output to the rated output power of the generator and is an indicator of its efficiency. The maximum theoretical value of kinetic energy extractable from the wind was demonstrated by Albert Betz and it is known as Betz's Law. The maximum coefficient of performance (Cp) in kinetic-energy extraction is 59.3%.

CASE STUDY

On studying the development of wind turbines in Egypt, a proposed location for an offshore wind farm would be next to the north coast lying on the Mediterranean Sea that extends within the regional water of Egypt. The proposed area lies offshore to the north east of Suez Canal due to the clear need for energy resources especially in the near logistically important areas. Moreover, the potential of wind energy there is very promising.

In this paper, SRWT and MRWT are studied. In addition, it is assumed that the produced output power is 5 MW for both types of the studied mills. Therefore, with the same 5MW output, stability and cost can be compared as shown in the methodology underneath. The studied severe loading cases on the mills in this paper include both stationary rotor case at cutoff wind speed condition, and the non-stationary case on having the rotors not stopping after being exposed to the cutoff wind speed, and the subsequent effect on the wind mill structure in both cases. Furthermore, a suggested modified design is introduced for MRWT to get better performance under the studied loads. The desired modification accounts for adding bracing members to the MRWT to reach an optimized performance.

Moreover, the foundations for both types, the SRWT and MRWT, are assumed mono-pile deep foundations. The assumed water depth within the offshore wind farm area is 25 m., and the wave height above water surface in stormy days is assumed reaching up to 3 m. The latter assumption with the assumed water depth is based on the warning issued by the Head Chief of Climate Forecast Institute in 31st December 2019 [6]. Furthermore, the extreme storm duration is assumed 10 hours for both types and with considering a fetch of the wind to sea surface of 200km producing a 6-meter wave height [7].

On studying the stability of the two types, the simulation assumes a cutoff wind velocity of 25m/s at the tower top corresponding to 90km/hr. The wind loads are assumed increasing gradually in a step-by-step manner till failure. Moreover, to get the over-strength factor needed to compare the different models structurally, the failure condition for both models was set to a displacement deformation limit or sometimes a strength limit depending on which of them is more critical.

METHODOLOGY

Modeling and Simulation:

For studying the two models, SRWT and MRWT, and to compare between them as per two main aspects: financially-wise and stability-wise, a 3D model for the structure-rotor system was created using ANSYS software. This is done with putting into consideration the following:

Using solid-shell (3D finite strain190) elements [8] that combine solid element with shell elements, as it is a bilinear material .The latter element are suitable for models of wind turbines [9]. Using nodes at upper and lower surface and using only displacement degrees of freedom allows calculating strains and stresses in thickness direction properly. In addition, the treatment of rotations can be avoided completely and the transition to full 3D-continuum parts is directly possible. Elements based on the Solid-Shell concept are now available using bilinear shape functions as well as using biquadratic shape functions in in-plane direction. [10]

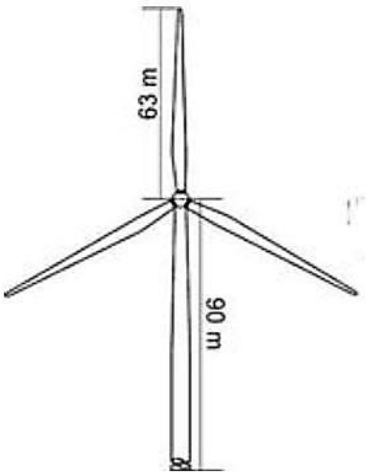


Fig. 3: Dimensions of SRWT

Properties of wind turbines

According to the National Renewable Energy Laboratory (NREL), a single rotor wind turbine 5MW, and a multi rotor wind turbine with 3 rotors, each rotor has three blades, are chosen [11,12]. The nacelle or hub is assumed at 90m height from the tower's base for the two types. The material for both types is assumed structural steel alloy ASTM A992, with a density of 7850 kg/m3, max yield strength of 345 MPa and ultimate tensile strength 448 MPa. The Young's modulus is 200 GPa and the shear modulus is 77 GPa [13].

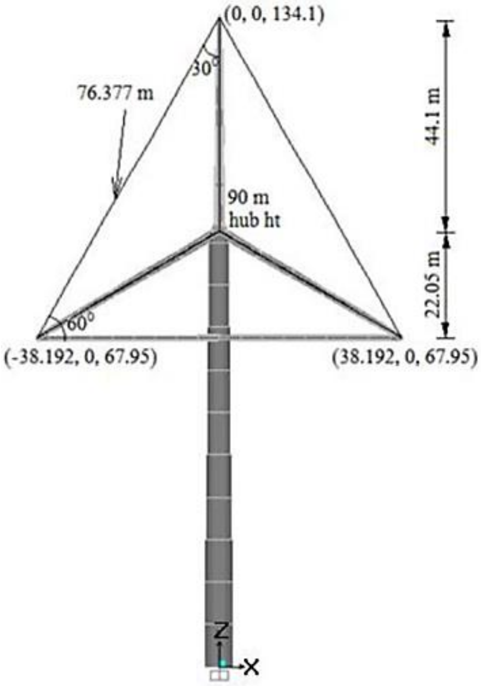


Fig. 4: Dimensions of MRWT

Properties of NREL 5 MW wind turbine

Single rotor wind turbine with three blades, hub is located 5m shifted to the tower centerline from the upwind side, and 90m height above ground. The center of mass for the nacelle is located 1.9 m to the downwind side of the tower's centerline and 1.75 m above it, which was half the height of the turbine's nacelle. The rotor and hub diameters are 126m and 3m respectively. The rated speed of the rotor is 12.1rpm. The base diameter of the tower is 6 m and thickness of 0.027 m. The top diameter is 3.87m and the steel thickness is 0.019 m. For MRWT, the height of the lower rotors is 67.95 m from the tower bottom. In contrast, the top rotor is 44m above the tower top with total height 131.6 m from the tower bottom. The distance between the centers of the rotors is 76.377m.

The center of mass for each hub is 2.89 m to the upwind side, and for each rotor is 1.1m to the downwind side. Rotor and hub diameters are 72.75m and 2m respectively. Rated speed of rotor is 20.94rpm. Table 1 shows the different parts masses in the SRWT and MRWT studied models. The dimensions of the different parts of the SRWT and the MRWT are shown in Table 2.

Table1: Different Masses for SRWT and MRWT

	NREL 5MW	**MRWT**
Total rotor mass(kg)	123,193	92,383
Total nacelle mass (kg)	234,608	132,526
RNA weight (kg)	357,801	74,972
Tower mass (kg)	347,460	347,460

Table2: Design dimensions data for SRWT and MRWT

	Single rotor wind turbine	**Per rotor of MRWT**
Rotor diameter (m)	126	72.75
Rated rotor power (MW)	5	1.67
Hub Diameter (m)	3	2
Rotor velocity(rpm)	12.1	20.94

Spars connect the hub of a rotor to the tower which requires less material than the case when there are horizontal and vertical frames connecting the rotors. The spar section is triangular as in table 3 which reduces the wind resistance of the structure and is a good design against bending relative to the rotor centroid.

Table3: Dimensions of spar sections as isosceles triangles along the spar height

Base (m)	Height(m)
0.6	1
0.8	1.2
1	1.4
1.2	1.6
1.4	1.8
1.6	2

Wind Turbine loads:

Aerodynamic Loads

The wind loads caused by air flow through blades are the drag and lift forces, whereas for the tower case, the wind is acting as shear forces as in tables 4,5 and 6 . The drag force results from viscous friction at blade surface and the resulting pressure difference, and acts parallel to the air flow. Meanwhile, lift force acts perpendicular to flow because of unequal pressure between the upper and lower surfaces of the blade [4]. The resultant of the lift and drag forces induces new forces namely the thrust force and torque force, as shown in figures 5,6,7 and 8.
Moreover, the effect of the earth's boundary layer where friction between the atmospheric air and the ground leads to a strong gradient in wind speed (wind shear), with wind increasing significantly with height above ground. The wind shear can be determined by the following equations [14],

$$v_H = v_{ref} * \left(\frac{H}{H_{ref}}\right)^{\alpha} \qquad \text{Equation (1)}$$

where:
v_H is the mean wind speed (m/s) at elevation H
v_{ref} is the mean wind speed (m/s) at reference elevation H_{ref}
H represents the height (m) above the ground
H_{ref} represents the reference height (m)
α is the shear exponent, assumed to be 0.2

The resulting air pressure is obtained as
$$P = 0.5\rho\, v^2 \qquad \text{Equation (2)}$$
Where: ρ is the air density of 1.225 kg/m^3

Table 4: Aerodynamic loads for rotors

			Thrust Force(KN)	Moment(KN.m)
Stationary	**SRWT**	**Single Rotor**	102.41	
	MRWT	**Top Rotor**	35.949	
		Right and Left Rotors	27.264	
Moving	**SRWT**	**Single Rotor**	271	4178
	MRWT	**Top Rotor**	106.17	800
		Right and Left Rotors	80.518	800

Table5: Shear loads for tower of SRWT and MRWT

Height from ground (m)	Force (KN)
5	9.408
15	12.1562
25	13.672
35	14.9
45	15.522
55	16
65	16.378
75	16.426
85	16.47

Table6: Shear loads for spars of MRWT

	Height from ground (m)	Pressure (Mpa)
Shear Forces on Right and Left Spars	70	3.47 e-4
	75	3.55 e-4
	80	3.65 e-4
	85	3.7 e-4
Shear Forces on Top Spar	95	3.92 e-4
	105	4.08 e-4
	115	4.24 e-4
	125	4.37 e-4
	135	4.5 e-4

Gravity Loads

Gravity Loads in this problem denotes the weights of rotor(s), blade(s), nacelle(s) and the tower. It is obvious that the own weights of both types of wind turbines will be the summation of all the bodies masses multiplied by the gravity acceleration. The applied weight loads on the two models are shown in Table 1.

Hydrodynamic Loads

The wave force which in this case is 182.05 KN can be calculated from the following Morison equation [15],

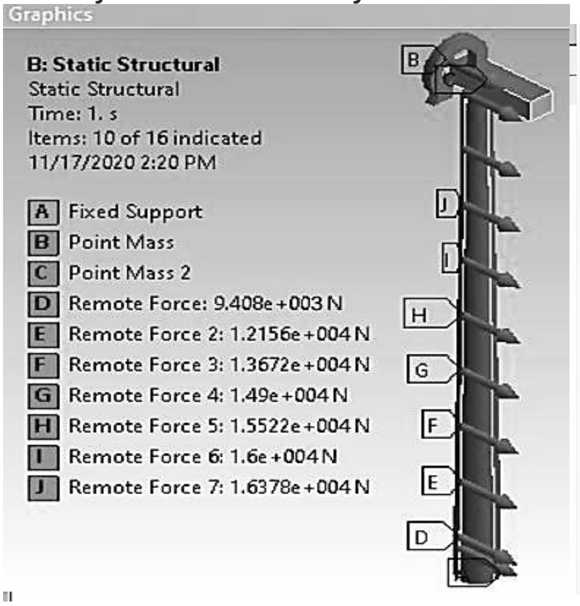
$$F = \frac{1}{2}\rho_w C_D D|U|U + \rho_w C_I A U' \qquad \text{Equation (3)}$$

Where:
ρ_w denotes water density, 1025 kg/m^3
C_D and C_I denote the drag and inertia coefficients,
D is the diameter of the structural member.
U and U' are horizontal velocity and acceleration of flow respectively.

Blade feathering effect

During blade rotation in high wind speeds, the wind turbine is subjected to excessive structural loads that increase the probability of failure. A great attention is required to preserve the manufacturing material from damage as well as cost reduction, thus, controlling aerodynamic loads in high wind speeds is very important [16]. In practice, blades rotations are stopped by controlling pitch angle of blade which is called feathering. This reduces the area of blades which faces the wind to prevent the rotor from rotating at speed higher than the cutoff speed. This concept protects the wind turbines from damage during in storms in case of offshore wind turbines.

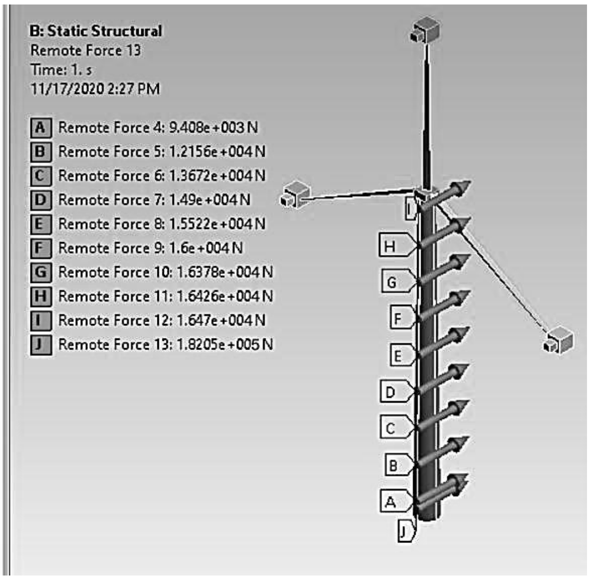
Aerodynamic loads in Ansys



B: Static Structural
Static Structural
Time: 1. s
Items: 10 of 16 indicated
11/17/2020 2:20 PM

- **A** Fixed Support
- **B** Point Mass
- **C** Point Mass 2
- **D** Remote Force: 9.408e+003 N
- **E** Remote Force 2: 1.2156e+004 N
- **F** Remote Force 3: 1.3672e+004 N
- **G** Remote Force 4: 1.49e+004 N
- **H** Remote Force 5: 1.5522e+004 N
- **I** Remote Force 6: 1.6e+004 N
- **J** Remote Force 7: 1.6378e+004 N

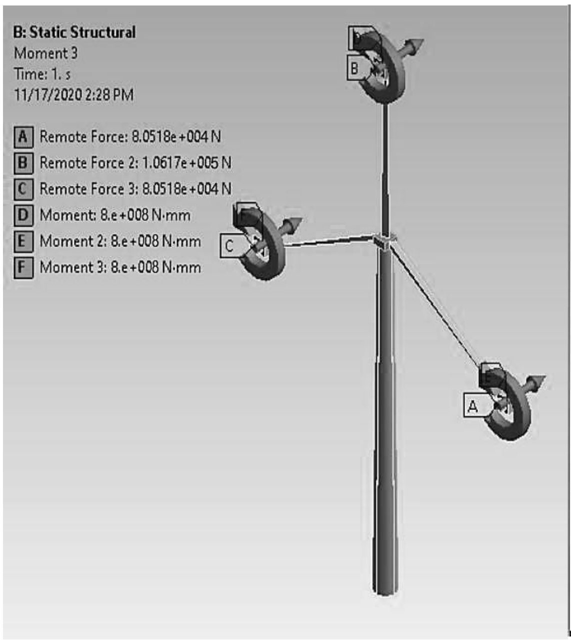
Fig. 5: Loads on SRWT



B: Static Structural
Remote Force 13
Time: 1. s
11/17/2020 2:27 PM

- **A** Remote Force 4: 9.408e+003 N
- **B** Remote Force 5: 1.2156e+004 N
- **C** Remote Force 6: 1.3672e+004 N
- **D** Remote Force 7: 1.49e+004 N
- **E** Remote Force 8: 1.5522e+004 N
- **F** Remote Force 9: 1.6e+004 N
- **G** Remote Force 10: 1.6378e+004 N
- **H** Remote Force 11: 1.6426e+004 N
- **I** Remote Force 12: 1.647e+004 N
- **J** Remote Force 13: 1.8205e+005 N

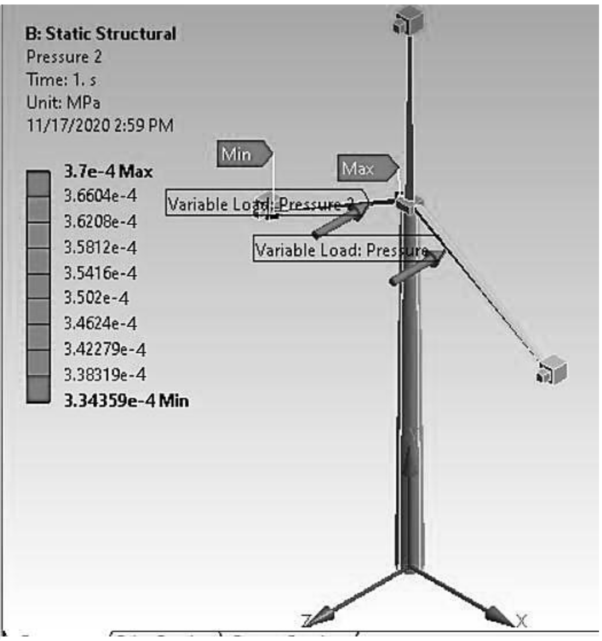
Fig. 6: Loads on MRWT's tower



B: Static Structural
Moment 3
Time: 1. s
11/17/2020 2:28 PM

- **A** Remote Force: 8.0518e+004 N
- **B** Remote Force 2: 1.0617e+005 N
- **C** Remote Force 3: 8.0518e+004 N
- **D** Moment: 8.e+008 N·mm
- **E** Moment 2: 8.e+008 N·mm
- **F** Moment 3: 8.e+008 N·mm

Fig. 7: Loads on MRWT's rotors



B: Static Structural
Pressure 2
Time: 1. s
Unit: MPa
11/17/2020 2:59 PM

3.7e-4 Max
3.6604e-4
3.6208e-4
3.5812e-4
3.5416e-4
3.502e-4
3.4624e-4
3.42279e-4
3.38319e-4
3.34359e-4 Min

Fig. 8: Pressure on MRWT's spar

ANALYSIS OF RESULTS

On running the simulation models in Ansys®, the maximum design loads as per [13] are considered occurring at the cut off wind speed level. The loads are applied in a step by step manner. The incremental loads are applied until reaching the ultimate strength limit or the ultimate strain limit whichever takes place in advance. It is noticed in the applications shown herein that the strain limits is always reached before the strength limits. For the case of the rotor not stopping at cutoff wind speed level, the incremental loads still increases till failure is achieved. The resulting stresses and deflections at the different load levels are shown in Tables 4 and 5.

Table 7: Results for stationary blades case

Stationary Blades				
	SRWT		MRWT	
Load	Deflection (m)	Max stress (MPa)	Deflection (m)	Max stress (MPa)
100% Cut off load	0.326	81.35	0.521	48.6
150% Cut off load	0.489	121.8	0.781	72.9
200% Cut off load	0.652	162.48	1.042	97.1
250% Cut off load	0.815	203	1.302	121.4
300% cutoff load	0.978	243.7	1.557	145.3
330% cutoff load	1.076	268	1.719	160.27
350% cutoff load	1.14	284.3	1.824	170
400% Cut off load	1.305	325	2.084	194.27
470% Cut off load	1.73	353	2.449	228.27
500% Cut off load			2.605	243
550% Cut off load			2.866	267
600% Cut off load			3.126	291.4
670% cut off load			3.491	325.4
700% cut off load			3.648	340

Table 8: Results for moving blades case

Moving Blades				
	SRWT		MRWT	
Load	**Deflection (m)**	**Max stress (MPa)**	**Deflection (m)**	**Max stress (MPa)**
100% Cut off load	0.75	153	1.129	88.8
150% Cut off load	1.135	229.8	1.7	133.26
200% Cut off load	1.5	306.4	2.241	175.8
230% Cut off load	1.726	351.8	2.597	204.3
250% cutoff load	1.879	383	2.823	222
300% cutoff load			3.388	266.5
330% cutoff load			3.727	293.18
400% cutoff load			4.517	355.36

Deflection limit of tower top

The maximum deflection is limited to 1.25% of height to avoid excessive motion of the turbine structure [17]. In case of stationary blades: For single rotor turbine, the maximum deflection is 1.14 m which occurs at load of 350%cutoff load. However, the deflection is about 1.7 m at the 330% of cutoff load in case of multi-rotor turbine. On the other hand, for the moving rotor case, the maximum deflections for SRWT and MRWT are at the same load that is about 150% cutoff load.

For stationary blades, strength failure occurs for single rotor turbine at a load of about 450% cutoff loads, and at 700% cutoff load in case of multi-rotor turbine showing more stability. As blades are rotating, failure occurs at a load of about 230% cutoff load for SRWT, and at a load of 400% cutoff load in case of MRWT.

Over strength factor (OSF)

The over strength factor is defined here in as the ratio between the yield shear stress (V_y) to the design shear stress (V_s)

$OSF = V_y / V_s$ Equation (4)

As this factor increases, the possibility of failure decreases [18]. On running the simulation, the MRWT has and OSF of 7 in the stationary case, and 4 in the moving rotor case. The latter results are higher OSF than the cases of the SRWT which are 4 and 2.3 respectively in the stationary and moving rotor cases, as shown in Figs. 9,10.

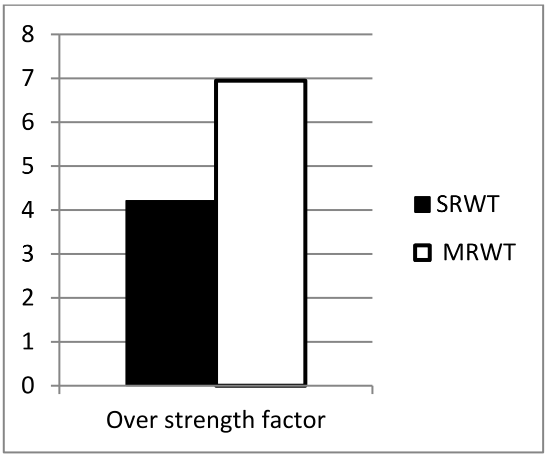


Fig. 9: Over strength factor For stationary case

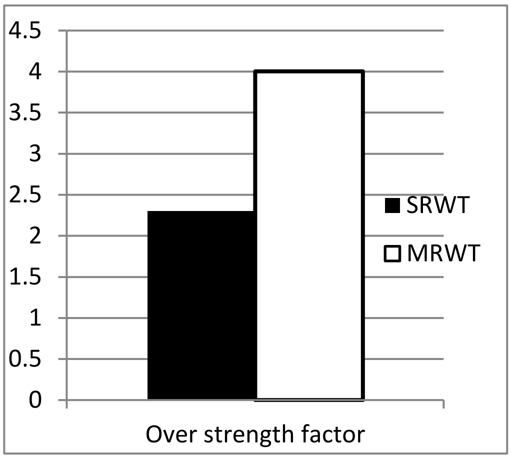


Fig. 10: Over strength factor for moving case

Stress-strain curve

The stress-strain curve in Fig 11 indicates that despite that the loads are different and the resulting deformations as well for both SRWT to MRWT, yet the stress-strain curve are the same for both. This practice was done in order to prove that the comparison between the SRWT and MRWT was not based in terms of material properties, thus, to indicate fair comparison difference.

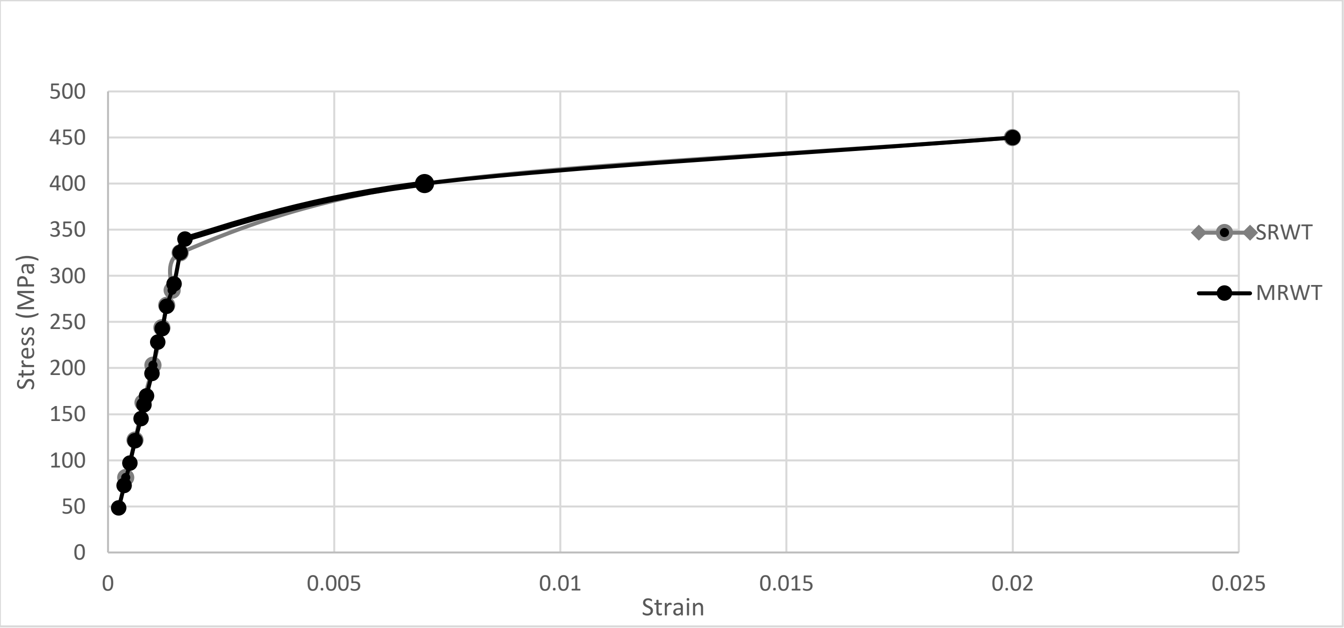


Fig. 11: Stress-Strain curve

In spite of that, the Load-Deformation curves in figures 12, 13 shows that at the same load while were for example 250% and 400% of the design load at stationary blades, yet MRWT has a higher deformation than SRWT. This indicates that the MRWT reach to the allowed deformation limit earlier than SRWT. The MRWT reach the failure limit at 330% of the designed load while SRWT reached failure limit at 350% of the designed load.

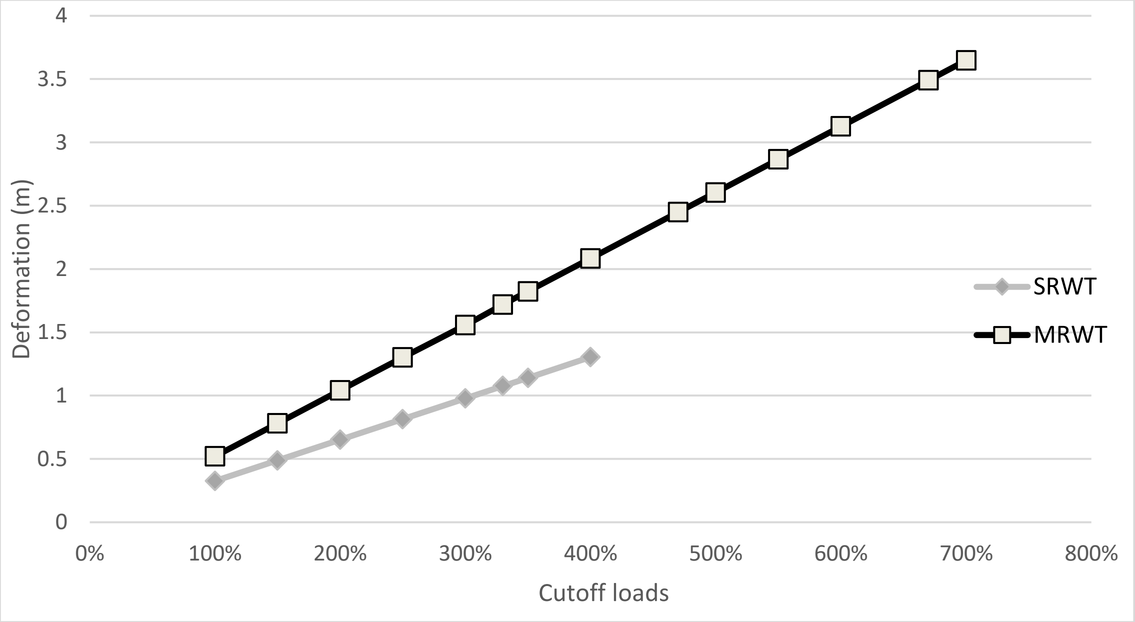


Fig.12: Load-Deformation curve for stationary blades case

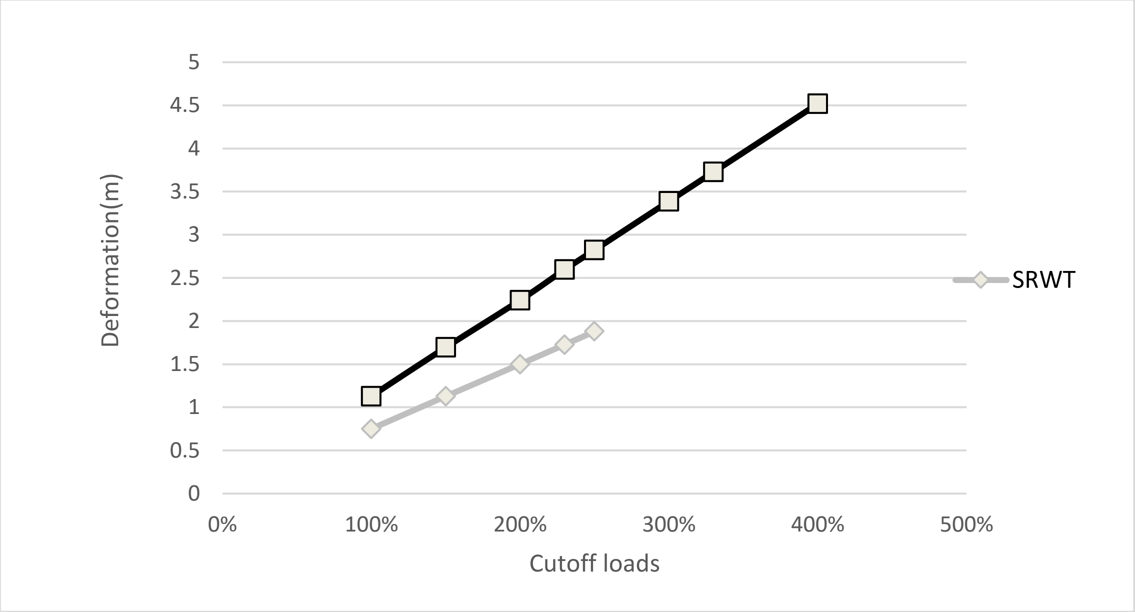


Fig. 13: Load-Deformation curve for moving blades case

Meanwhile to study the stress difference, an equivalent stress – load curve was made as shown in Fig.14 and Fig.15 as the loads increase. Consequently, it is shown that although MRWT is exposed to higher loads than SRWT it may have better stress distribution.

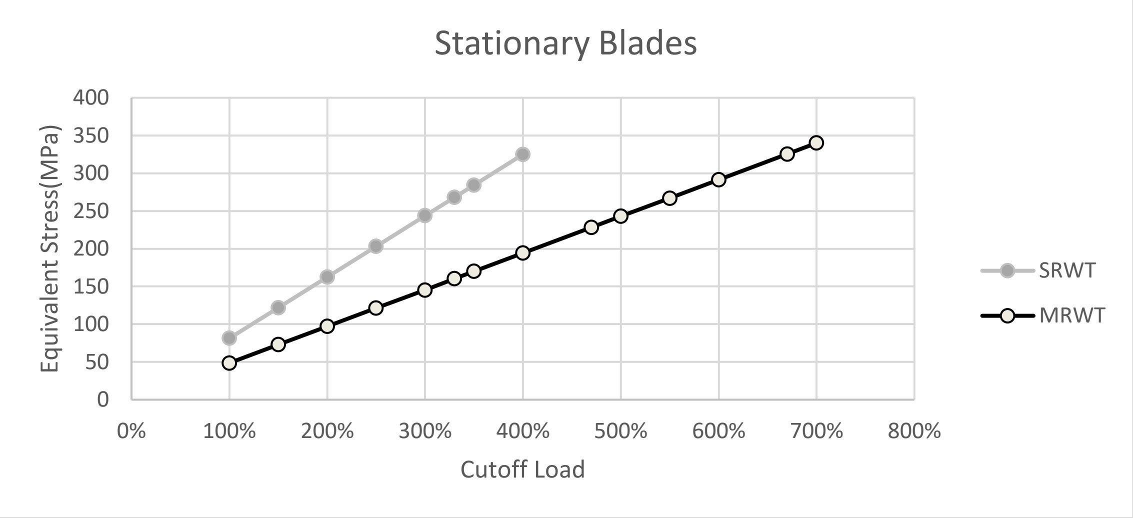


Fig. 14: Equivalent Stress-Load curve for stationary blades case

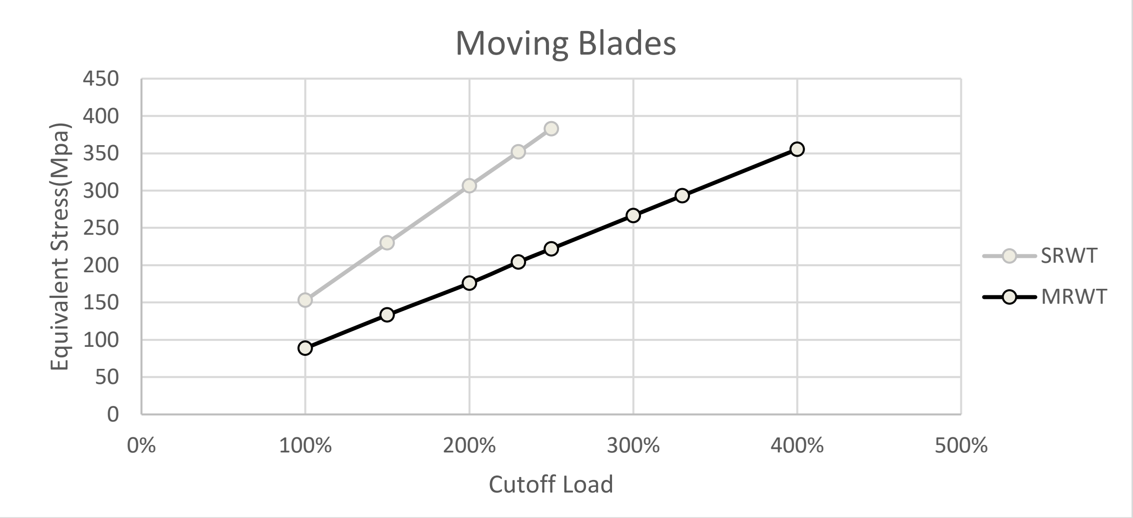


Fig. 15: Equivalent Stress-Load curve for moving blades case

In addition, the Equivalent Stress-Load curve shows that the SRWT has bigger slope than the MRWT. This may be attributed by the fact that the area subjected to the load is smaller thereby yielding a higher stress. From results, the MRWT can withstand loads more than SRWT, and the maximum deflection is approximately at loads close to each other. However, as the MRWT is lower in weight and may resist higher loads, this consequently leads to clear increases in the deformations at the spars end. This is an annoying issue especially on considering the resulting fatigue effects. Accordingly, to overcome such a problem and to find the optimum design, a bracing system is proposed as shown in the following section.

Bracing System

The bracing system proposed is composed of two diagonal spars as shown in Fig. 16. Such spars added to the MRWT are attached to each of the three main spars holding the nacelles. The bracing spars link the main spars at the point at two thirds of each spar length, leaving only one third at the end of the main spars, as shown in Fig.16.
After applying the bracing, the deformation of MRWT at 330% of the cutoff load, (which was the load of maximum allowed deflection for MRWT) became 1.47m instead of 1.71 m before, and the load that exceeds the allowable deflection in MRWT is 400% with deflection of 1.7m. Moreover, this exceeds SRWT maximum load for allowable deflection of 350 % cutoff load with 50% more, with enhancing the total load bearing by 14% better than SRWT best loading for deflection in the stationary mode and 33% in the moving blades case.

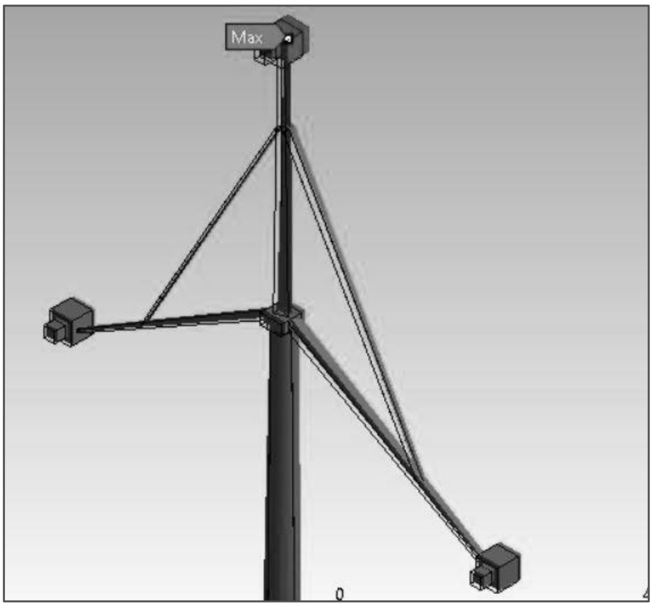


Fig 16: bracing spars for MRWT

Figures 17 and 18 show that the corresponding deformations of the braced MRWT became smaller for the same cutoff load multiples and very close to the deformations of the SRWT case indicating a robust performance and a more stable condition.

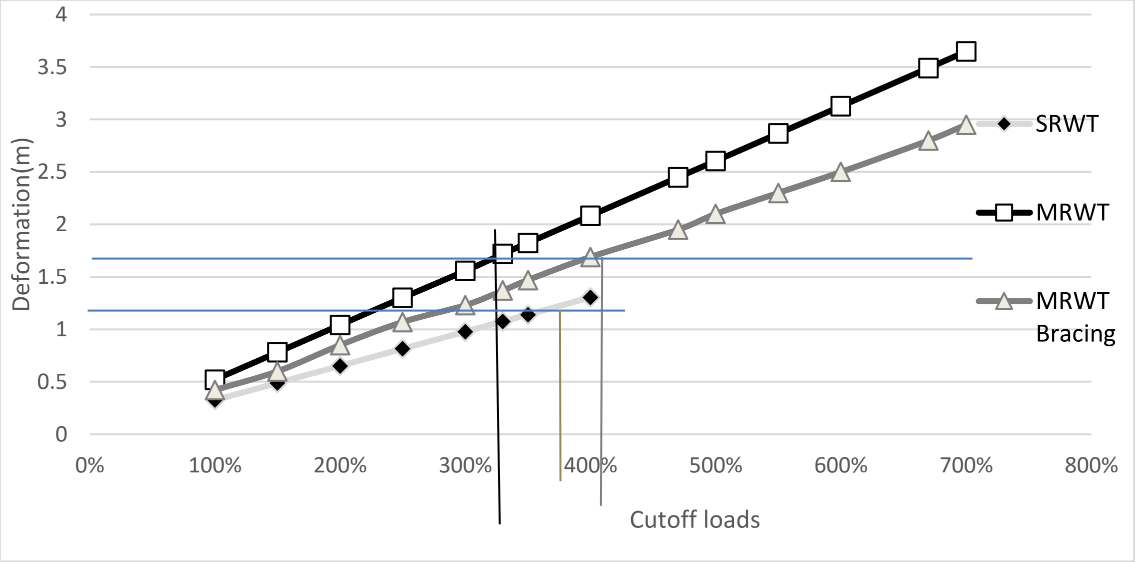


Fig 17: Load-Deformation curve for MRWT with proposed bracing (Stationary blades case)

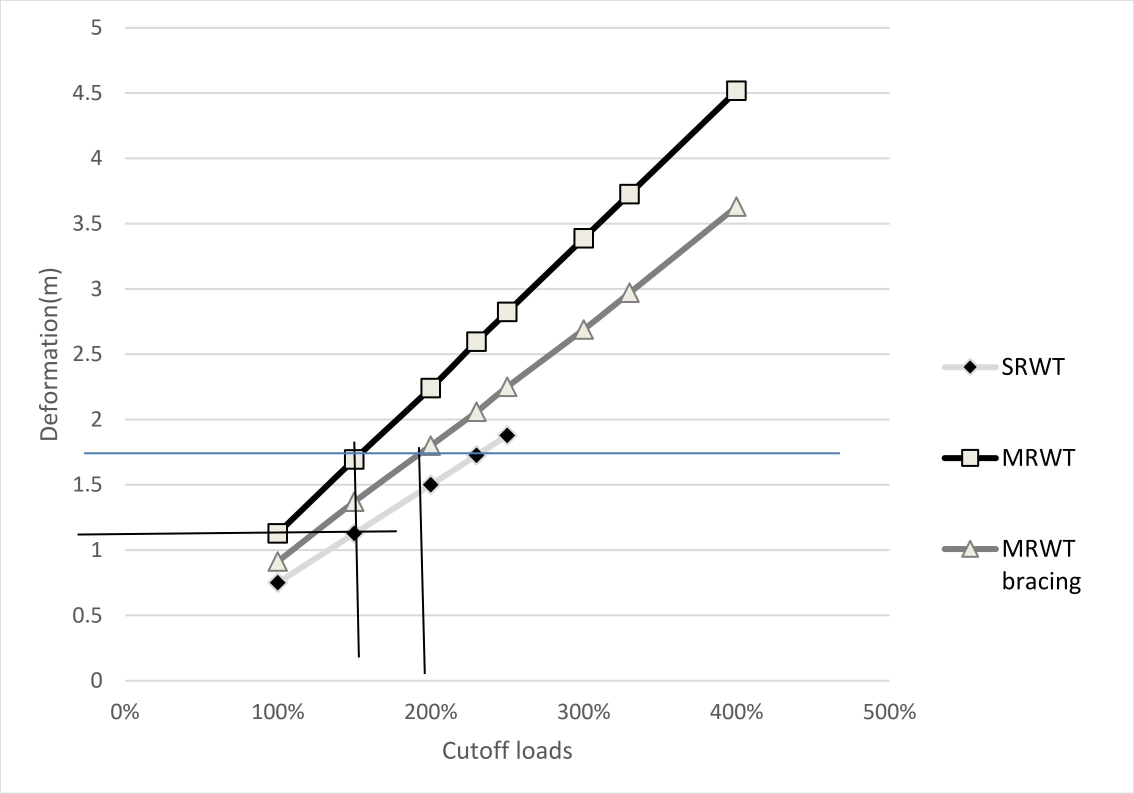


Fig 18: Load-Deformation curve for MRWT with bracing (Moving blades case)

COST EFFICIENCY

As The MRWT showed a better performance than the SRWT in the stability, especially after the bracing. However, an economic wise should be studied to determine the optimized offshore wind turbine. Wind turbine costs are determined by equations controlled by size and mass of wind turbine's parts [13, 19]. These equations cover every aspect and stage the offshore wind turbine goes through, from being just a thought till the annual life time maintenance and repairing. Cost comparison between SRWT and MRWT about every aspect is listed in Table 6 [13, 19].

Table 9: Comparison of Cost for SRWT and MRWT

	SRWT	**MRWT**
Total cost of blades	810908.5176	521488.4164
Hub cost	127994.7649	133362.3598
Total pitch system cost	183551.547	103.716288
Power electronics cost	395000	395790
Total yaw system cost	113953.5842	65085.53334
Hydraulics, cooling system cost	60000	60120
Nacelle cover cost	61534.7	69349.47
Mainframe cost	120017.3743	120701.3331
Nose cone cost	10084.485	13560.165
Low speed shaft cost	11581.63206	6906.216233
Total bearing system cost	95049.63485	39615.27917
Gearbox cost	685771.5085	522949.834
Brake/coupling cost	9946.773009	9966.213028
Generator cost	325000	325650
Spars cost	-	175145
Foundation cost	1500000	1584000
Transportation cost	1312250	198897.6
Port and staging equipment	100000	105600
Offshore turbine installation	500000	528000
Offshore electrical interface and connection cost	1300000	1372800
Offshore permits, engineering, and site assessment cost	185000	195360
Annual offshore Levelized Replacement Cost (LRC)	85000	89760
Annual offshore Operation and Maintenance (O&M)Cost	876000	876000
Personnel Access Equipment	60000	60000
Scour protection	275000	275000
Marinization	381631.9692	262819
Total	**9585276.49 $**	**8008030.136 $**

The cost is then escalated using the PPI (Producer Price Index) to the desired year for money value. However, the unit to compare between both types of wind turbine should be ($/KW) as equation 4. [19]

Equation (4)$\mathrm{COE} = \frac{Total\ cost}{AEP}$

Where
COE: Cost of energy ($/KW).
AEP: net annual energy production (kWh/year).

Cost of energy for SRWT is about 0.218 $/KW and for MRWT is 0.182 $/KW.
This indicates that the MRWT is almost about 16.5 % more economical than SRWT.

CONCLUSION

This paper presented stability–based comparison between single rotor NREL 5MW wind turbine and NREL MRWT that contains three rotors 1.67 MW wind turbine in extreme loading conditions using Ansys software program. The comparison was made in two cases. The first case is at cutoff wind speed with stationary rotors. The second case is at cutoff wind speed with moving rotors. Moreover, to determine which type of models will be used to get the best of an offshore wind farm, an over strength factor was calculated for both models by exposing the two models to an incremental increasing load to reach either failure by strength limit or deflection limit. The MRWT showed a better stress distribution than the SRWT in both cases of the stationary and moving rotors. However, The MRWT model showed higher deflection that may lead to earlier fatigue and thereby shorten the assumed life time of an offshore wind turbine.

Accordingly, a bracing system was developed for the MRWT model to reduce the extreme deflection. It was shown that the proposed bracing reduced the deflections to accepted measures which resulted in increasing the maximum strength load up to 14% better than SRWT in the stationary rotor case, 30% in the moving rotor case. Besides, it is shown that the MRWT model is 16.5% cheaper than SRWT model on putting the long run costs into consideration. Furthermore, the cost of energy for the SRWT model is found to be about 0.218 $/KW and that for MRWT model is found to be about 0.182 $/KW for offshore wind turbines. Based on all above, on deciding to establish an offshore wind farm, MRWT three-rotor model may be more stable, durable and cheaper than the SRWT model on producing the same amount of energy. This is the case after putting the bracing system on the MRWT model.

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